load, as an effective average load impedance (R_{in}) annotated in FIG. **8** using the following equation:

$$R_{in} \simeq \frac{V_{in}^2}{2P_{load}} \eta_{AC-DC}, \tag{2}$$

where V_{in} is the peak input rectified voltage. As a first-order estimation, when assuming a peak input of 2 V and η_{AC-DC} of ~80%, the effective resistance can be computed from (2) to be between ~200 kΩ and ~2 kΩ for 10 μW to 1 mW load powers. An input voltage of 2V is assumed since it is much greater than typical CMOS thresholds, allowing for high η_{AC-DC} (>80%) while also remaining below typical CMOS technology voltage limits. This calculation and the approximations are sufficient for our purpose of getting a first-order estimate of the effective implant load since modest differences do not greatly influence the PME and further refinements can be made using circuit simulators.

[0067] In order to achieve a high PME over the wide range of R_{in}, a power receiver should exhibit a similar impedance range as R_{in}. FIG. **9** shows an example measured impedance profile of a mm-sized ultrasonic receiver made from Lead Zirconate Titanate 5H (PZT5H), a piezoelectric material, with dimensions of 1.5 mm×1.1 mm×1.1 mm. As seen in the figure, there is nearly two orders of magnitude change in the real part of the impedance (R_{piezo}) between the short-circuit (f_{sc}) and open-circuit (f_{oc}) resonances. The large value and range of R_{piezo} offers a significant advantage for powering various P_{load}. With the appropriate design methodology to choose material and dimensions of the ultrasonic receiver, R_{piezo} can be tuned to match the targeted R_{in} range. Furthermore, we can leverage the inherent inductive nature of a piezoelectric receiver operating around mechanical resonance, in a band hereinafter referred to as the inductive band (IB), for impedance matching to obtain high PME. Conventionally, passive reactive components are used in order to perform impedance matching. Though large inductance around MHz is not practical when the form factor of implantable device is limited to mm-dimensions, capacitance is easy to obtain in a small volume or even on chip. The large inductive reactance with a reasonable quality factor in the IB, allows for impedance transformation with purely capacitive matching networks. Depending on the operating frequency and the topology of the matching network, the required matching capacitance ranges only from ~1 pF to 40 pF. The details of the matching network design will be described in section B5.

B3) Ultrasonic Receiver Design for IMDs

[0068] In this section, we focus on how to obtain the impedance behavior discussed in Section B2 by introducing a first-order circuit model that aids with the design process. The model provides sufficient accuracy for capturing the frequency behavior of the impedance and the radiation resistance of the piezoelectric receivers.

B3a) Ultrasonic Receiver Modeling

[0069] We use the one-dimensional series circuit model shown in FIG. **10** for first-order design of the piezoelectric receivers around fundamental resonance. The model has a series RLC tank with the intrinsic capacitance of the device (C_0) in shunt. The circuit element values are determined by width (w) and thickness (t) of the device, the piezoelectric material properties: relative permittivity ($\in^T$), electrical-mechanical coupling constant (k_{33}), acoustic impedance of the material (Z_C), front acoustic loading (Z_F), and back acoustic loading (Z_B). The model is more accurate when Z_F, Z_B<<Z_C. This condition is satisfied in the design as the front of the device is loaded by tissue (Z_{tissue} ≃1.4-1.6 MRayls) when implanted in the body, and the receiver is designed with air backing (Z_{air} ≃400 Rayls) to minimize the effect of mechanical damping. Using this model, we investigate four different materials, PZT4, PZT5H, Barium Titanate ($BaTiO_3$), and Lithium Niobate ($LiNbO_3$), and compare their performances as ultrasonic receivers for IMDs. PZT4 and PZT5H are common piezoelectric materials widely utilized in imaging and sensor transducers. $BaTiO_3$ and $LiNbO_3$ are lead-free piezoelectric materials and are potentially biocompatible. The material properties, assuming length-expander bar mode (LE mode) operation, are listed in Table I. LE mode is utilized here as it provides better approximation when the aspect ratio of the receivers (G=w/t) is constrained below unity in order to reduce the overall implant volume.

TABLE I

Material properties for length expander bar mode

	PZT4	PZT5H	$BaTiO_3$	$LiNbO_3$
Density, ρ (kg/cm3)	7500	7500	5700	4640
Sound velocity, v (m/s)	4100	3850	5000	6400
Acoustic impedance, Z_C (MRayl)	30.8	28.9	28.5	29.7
Electro-mechanical coupling coefficient k_{33}	0.70	0.75	0.5	~0.5
Relative Permittivity ϵ^T	1300	3400	1700	30
Mechanical Quality Factor	500	65	300	>1000

B3b) Selection of Dimensions and Materials for Receiver

[0070] The thickness of the receivers, t, and the sound velocity of the piezoelectric materials, v, are the main parameters for positioning the fundamental resonance. The f_{oc} and f_{sc} for G<<1 are given as,

$$f_{oc} = \frac{v}{2t}, \tag{3}$$

$$f_{sc} \simeq \sqrt{1 + \frac{8k_{33}^2}{\pi^2}}\, f_{oc}, \tag{4}$$

where f_{sc} is lower in frequency than f_{oc}, and they are related by k_{33}, which in turn determines the span of the IB. The resonance frequencies are inversely proportional to thickness of the material; thus, thinner devices have higher operating frequency. Due to mode coupling from finite width, the fundamental resonances will shift to slightly lower values for a practical aspect ratio. A correction factor of 1 to 0.7 for G≤1 can be inserted into (3) and (4) for more accurate determination of resonances. Nonetheless, this small shift does not have significant impact on the design process.

[0071] We aim to operate the devices with an IB between ~1-2 MHz as a trade-off between acoustic propagation losses through soft tissue (~1 dB·MHz/cm) and overall